THE NEUTRAL GAS DESORPTION AND BREAKDOWN ON A METAL-DIELECTRIC JUNCTION IMMERSED IN A PLASMA

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ABSTRACT

New results are presented of an experimental study and theoretical analysis of arcing on metal-dielectric junctions immersed in a low-density plasma. Two samples of conventional solar arrays have been used to investigate the effects of arcing within a wide range of neutral gas pressures, ion currents, and electron number densities. All data (except video) were obtained in digital form that allowed us to study the correlation between external parameters (plasma density, additional capacitance, bias voltage, etc) and arc characteristics (arc rate, arc current pulse width and amplitude, gas species partial pressures, intensities of spectral lines, and so on). Arc sites were determined by employing a video-camera, and it is shown that the most probable sites for arc inception are triple-junctions, even though some arcs were initiated in gaps between cells. The effect of surface conditioning (decrease of arc rate due to outgassing) was clearly demonstrated. Moreover, a considerable increase in arc rate due to absorption of molecules from atmospheric air has been confirmed.

The analysis of optical spectra (240-800 nm) reveals intense narrow atomic lines (Ag, H) and wide molecular bands (OH, CH, SiH, SiN) that confirm a complicated mechanism of arc plasma generation. The rate of plasma contamination due to arcing was measured by employing a mass-spectrometer. These measurements provided quite reliable data for the development of a theoretical model of plasma contamination. In conclusion, the arc threshold was increased to above 350 V (from 190 V) by keeping a sample in vacuum (20 μTorr) for seven days. The results obtained are important for the understanding of the arc inception mechanism, which is absolutely essential for progress toward the design of high-voltage solar arrays for space applications.

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INTRODUCTION

The current paper is a continuation of our study [1-5] of arc inception on a triple-junction with a conductor negatively biased with respect to the surrounding plasma. Previous experiments have clearly demonstrated that an electrostatic discharge occurs when the electric field strength is approximately 1 MV/m, which is almost one order of magnitude lower than is needed for initiation of a vacuum arc [6]. In order to explain this fact we suggested that the ionization of adsorbed gas (water vapor) plays the main role in the generation of initial plasma cloud and the plasma sheath which lead to the enhancement of an electric field. Two field enhancement mechanisms, protrusions on a metal surface and plasma polarization, can provide a high enough electric field (1-2 GV/m) to generate cold emission current with the density $10^{11}-10^{12}$ A/m^2. The plasma conductivity allows an electric current of 10-50 A, depending on the conditions of the experiments, to discharge a negatively biased electrode for short time intervals (10-50 μs).

A simple model of a discharge quenching due to water ions dissociative recombination has been developed, and its prediction of the relation between pulse width and capacitance $(\tau \propto C^{1/2})$ is confirmed for a wide range of parameters (C=0.01-1 μF, U=300-800 V). Moreover, hydrogen and hydroxyl spectral lines were observed in emission, and measurements revealed strong correlations between the intensity of H_α line and the value of the initial electrical charge. The observation of metal (Ag, Cu) spectral lines is an unarguable argument in favor of a high density Fowler-Nordheim current heating a metallic protrusion to very high temperatures. Together with the observed decrease of arc rate with number of arcs (conditioning) and a considerable rise of arc threshold for a sample that has been kept under high vacuum for a few days, all these details can be incorporated in a cohesive model of arc inception.

It should be noted that the role of electron impact desorption of water molecules was thoroughly discussed almost ten years ago [7,8], and the

increase of arc rate due to increase of water vapor partial pressure was confirmed by experiment [9].

The current paper is devoted to the analysis of experimental data containing optical emission spectra of arc plasmas and mass spectra of a low-density plasma contaminated by species emitted from arc sites. The results obtained with these techniques are in a quite good agreement with each other. Both methods revealed the presence of water-ion dissociative recombination products - hydrogen and hydroxyl - in respective plasmas. The incorporation of these new data in a simple model of ionization balance in an arc plasma made it possible to estimate the number of water molecules emitted in the surrounding plasma due to the discharge on triple junction.

2. CHEMICAL COMPOSITION OF ARC PLASMAS

Experimental setup is described in all details in Refs.[4,10]. Optical spectra measurements were performed in a small vacuum tank (45 cm diameter and 75 cm height) installed at the NASA Glenn Research Center. Vacuum equipment provided pressures as low as 10^{-7} Torr. A Penning source generated an argon plasma with the electron density $n_e=(2-20)10^5$ cm^{-3} , temperature $T_e=2-5$ eV, and neutral argon pressure $p=(5-80)10^{-5}$ Torr, which could be adjusted during the experiment. Two solar array samples consisting of nine Si cells each were prepared. These 2x4 cm cells were connected in three parallel branches with three cells in series for each one. All cells were mounted on a fiberglass base. One of the two samples was mounted vertically in the center of the chamber, and it was biased by a high voltage power supply through a 10 kΩ resistor.

Diagnostic equipment included one spherical Langmuir probe with diameter $d=2$ cm, one current probe to measure arc current, a voltage probe, an intensified CCD camera with spectrometer, and a video camera for recording arc images and arc sites. The exposed sides of contacts and connecting wires were insulated by RTV and Kapton strips. Because the sample itself had a low capacitance, an additional capacitor was installed between the sample and ground. This allowed us to locate arc sites visually.

The measurements of mass spectra were performed in a large vacuum chamber (1.8 m diameter and 2.5m length) by employing a quadruple mass spectrometer. It should be stressed that the plasma parameters were practically identical in both chambers. One example of arc plasma optical spectra is shown in Fig.1. The ratio of number densities of

excited atoms can be derived from these measurements:

$$X = \frac{N^*(H)}{N^*(M)} = \frac{I(656)}{I(328)} \cdot \frac{\eta(328) \cdot A}{\eta(656) \cdot A_{32}} \qquad (1)$$

where $N^*(M)$ is the number density of exited metal atoms (Ag), $I(\lambda)$ is the observed line intensity, A_{ik} is the transition probability, and $\eta (\lambda)$ is the photocathode quantum efficiency.

Substituting measured intensities in Eq.(1) results in the following estimate: $X=0.6-0.7$. The degree of ionization of water molecules Y and silver atoms Z can be estimated from the simple model of ionization balance: $Y=0.01-0.04$, and $Z=0.1-0.2$ (see Ref.5 for details). According to experimental study of vacuum arcs with silver cathode, an average ion charge is $Q=2.14$, and an erosion rate is about 10^{17} ions(Ag)/C [11]. On the other hand, computer simulations and direct measurements show erosion rates about 100 μg/C [6,12], which correspond to a degree of ionization of silver atoms $Z=0.15$ in very good agreement with the estimate obtained from optical spectra. Taking into account differences between the ionization degrees for metal atoms and water molecules, one can estimate the rate of water emission from an arc site as $R=(3-6)10^{18}$ mol/C. However, according to Ref. 13, the electron impact desorption efficiency is about 0.02-0.05 molecules/electron, which corresponds to at least one order of magnitude lower R. The integrations of current pulse wave forms over time provide numbers for lost charges (Fig.2). The analysis of a few hundred measurements shows that a simple estimate for a lost charge

$$\Delta q = \int I(t)dt = (0.8 - 0.9) \cdot CU \qquad (2)$$

is valid within a wide range of capacitances C and bias voltages U . Thus, it seems possible to estimate the number of water molecules N ejected from the arc site for each experiment. For example, arc plasma optical spectra (Fig.1) and mass spectra of low-density plasma (shown below) were obtained with bias voltages $U=250-1000$ V and capacitance $C=1$ μF. In these conditions, simple calculations result in the following:

$$N = R \cdot \Delta q = (0.5 - 2.5) \cdot 10^{15} \qquad (3)$$

The last result is very important because it demonstrates with a high degree of certainty that the water adsorbed on a dielectric side surface does not form a monomolecular layer, and the exposure of an array to a high vacuum and/or high temperature can cause "drying" of triple junctions that leads to a rise of arcing threshold voltage.

Two more observations support the hypothesis of desorbed water ionization as the main source of the arc development: a) one triple junction can experience 15-20 arcs being biased at fixed voltage when the capacitance is low ($C=0.01$ µF), but the same junction arcs only 3-5 times with bigger capacitance ($C=1$ µF); b) the intensity of the hydrogen spectral line (H_a) increases with increasing lost electrical charge (Fig.3).

It seems reasonable to estimate the number of hydrogen atoms in the arc plasma by using measurements of H_a line intensities. The number of quanta radiated by excited hydrogen atoms per second is

$$\frac{dN_a}{dt} = A_{23} \cdot N_H^*(t) \qquad (4)$$

The number of quanta entering the spectrometer window during one pulse can be calculated as the following:

$$\Delta N_a = A_{23} \overline{N}_H^* \Delta t \cdot \frac{hd}{2\pi D^2} \cdot \beta \qquad (5)$$

where $d=50$ µm and $h=1.2$ cm are the width and the height of the slit respectively, Δt is the arc current pulse width, $D=40$ cm is the distance between the arc site and the slit, and $\beta=0.9$ is the transparency of the vacuum chamber window.

The number of quanta entering the CCD is expressed by the formula [14]:

$$\frac{\Delta N_{cn}}{\Delta N_a} = \xi \frac{h \cdot \Delta\lambda}{16f \cdot s} \qquad (6)$$

where $\Delta\lambda$ is the spectrometer resolution, $f=25$ cm is the spectrometer focal distance, $\xi \approx 0.1$-0.3 is the factor accounting for light absorption/reflection, and $s=1/1200$ mm is the spectrometer grating.

The measured intensity can be written as

$$I = \eta \cdot g \cdot j \cdot \Delta N_{cn} \qquad (7)$$

where $\eta=3$ is the photocathode efficiency for $\lambda=656$ nm, $g=128$ is the electronics gain, and $j=30$ is the number of CCD horizontal rows used in current measurements.

Finally, after simple algebra, the average number of excited hydrogen atoms can be expressed by the following formula:

$$\overline{N}_H^* = \frac{32\pi \cdot D^2 fs}{\eta g j \xi \beta dh^2 \Delta\lambda \cdot A_{23} \Delta t} I \qquad (8)$$

To obtain an estimate for the number of excited hydrogen atoms one can disregard the differences in arc pulse widths for different intensities. Then, Eq.8 transforms into the simple relation

$$\overline{N}_H^* = 10^7 \cdot I \qquad (9)$$

Thus, measurements of optical spectra indicate the number of excited hydrogen atoms of 10^{10}-10^{11} (see Fig.3). This last result is in excellent agreement with an estimate of the number of desorped water molecules (Eq.3) and the degree of ionization ($\sim 10^{-2}$) calculated in Ref.5.

The rate of the background plasma contamination caused by arcing was also measured by employing the quadruple mass spectrometer. Several examples of mass spectra are shown in Fig.4. It seems reasonable to develop a simple analytical model of this process to compare the results of optical and mass spectrometry. The rate of plasma contamination by ejected molecules (atoms) is determined by the following equation:

$$\frac{dN(t)}{dt} = R \cdot \Delta q \cdot r - \alpha \cdot N(t) \qquad (10)$$

where $N(t)$ is the number of ejected molecules (atoms) in surrounding plasma, and α is the pumping rate.

The solution of this equation is simple

$$N(t) = \frac{R \cdot \Delta q \cdot r}{\alpha} \cdot \left(1 - e^{-\alpha t}\right), \qquad (11)$$

and it provides the possibility to determine parameter α from the measured dependence of partial pressures vs. time: $p(t) \propto N(t)$ (Fig. 5). It is clearly seen that the partial pressure of atomic hydrogen grows considerably, while the partial pressures of other components stay practically steady. The increase in partial pressure of species i due to arcing can be expressed by the following formulae:

$$W(p_{ib}, r) = \frac{p_i}{p_{ib}} = \frac{R_i \Delta q}{\alpha} \cdot \frac{rkT_b}{p_{ib} V} \qquad (12)$$

where T_b is the background gas temperature, p_{ib} is partial pressure of respective component in the background gas, $k=1.38 \times 10^{-16}$ ergs/K is the Boltzmann constant, and V is the vacuum chamber volume.

The first stage of measurements was performed with bias voltage $U=-600$ V, and arc rate $r=0.5$-1

arc/s. As one can see in Fig.6., a real chance to register an increase in partial pressure exists for species with background partial pressure lower than 2.5 μTorr. This observation explains the well-expressed trend registered for hydrogen partial pressure (Fig.7). At the same time, it is difficult to measure changes in water vapor partial pressure because its initial concentration is high: $p=2.5$ μTorr. Thus, the measurements of mass spectra confirm the presence of atomic hydrogen in the arc plasma. Moreover, the measured increase of hydrogen partial pressure is in a quite good agreement with the analytical estimate (12), and this result can be considered as one more argument in favor of the arc inception model developed in Ref.5.

3.CONCLUSION

The considerable decrease of arc rate due to solar cell heating was demonstrated almost ten years ago [9]. In that paper, the authors suggested that the evaporation of water molecules from the dielectric side surface could be responsible for the observed effect. Recently, new evidence was obtained to confirm the role of water vapor in the arc initiation process [4,5]. The results shown in the current paper leave no doubts that adsorbed water must be removed from the dielectric surface in order to achieve a high arcing threshold. Hence, it seems possible to raise operating voltages up to 300 V for conventionally designed solar arrays, and to avoid arcing on their surfaces, by thoroughly outgassing all dielectric surfaces. Of course, much work lies ahead to determine the rate of outgassing, critical temperature, influence of radiation, and other parameters that depend on the specific array design.

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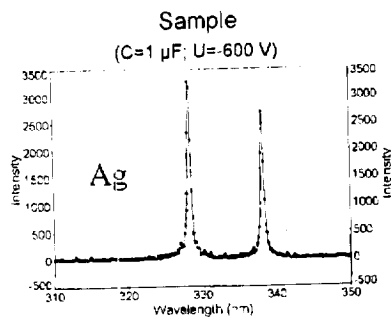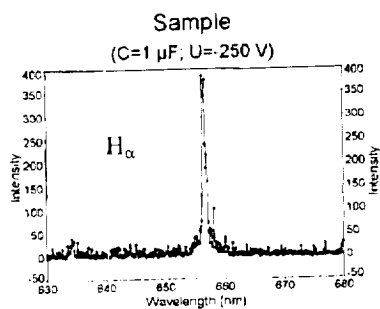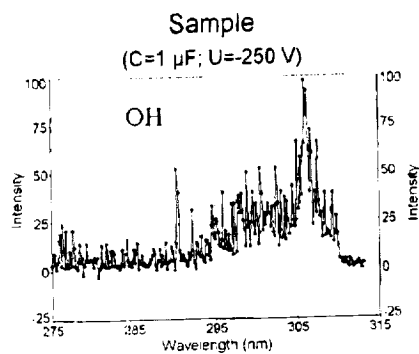
Sample
(C=1 μF; U=-250 V)

OH

Intensity vs. Wavelength (nm)

Sample
(C=1 μF; U=-250 V)

H_α

Intensity vs. Wavelength (nm)

Sample
(C=1 μF; U=-600 V)

Ag

Intensity vs. Wavelength (nm)

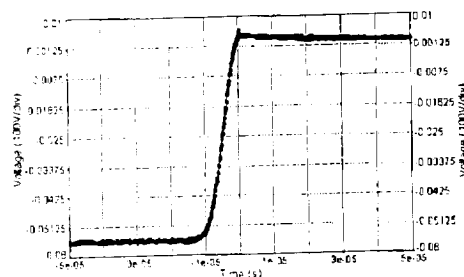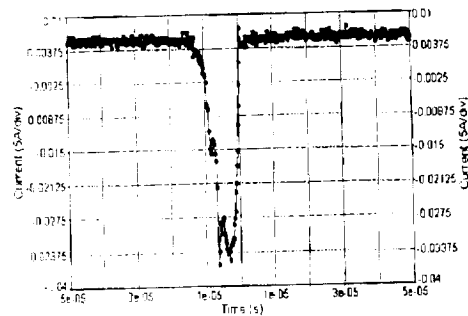**Fig.1.** Arc spectra demonstrate the presence of hydroxyl, hydrogen, and silver in the arc plasma.

Current (5A/div) vs. Time (s)

Voltage (100V/div) vs. Time (s)

Fig.2. Arc current pulse and capacitor voltage are shown for the discharge with bias voltage -700 V and capacitance 1 μF.

Halpha Intensity vs. charge
$y=a+bx^2$
$R=0.657, a=525, b=0.3222$

Line intensity vs. Lost charge (μC)
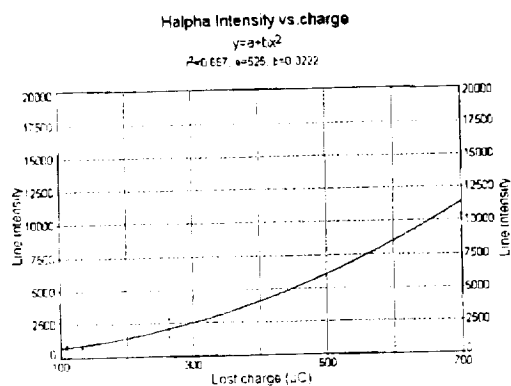
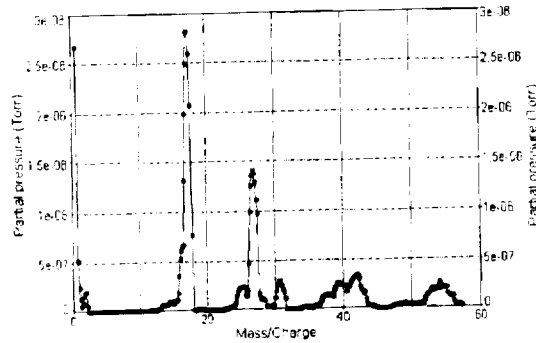**Fig.3.** The intensity of H_α spectral line depends on bias voltage and capacitance rather strongly.
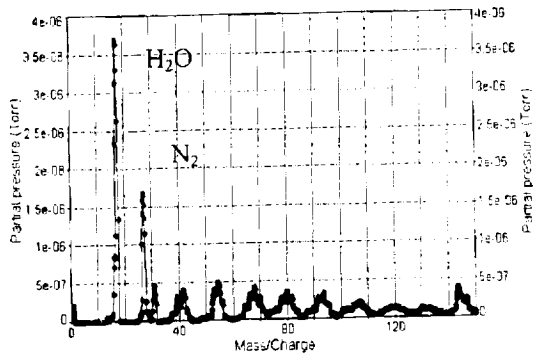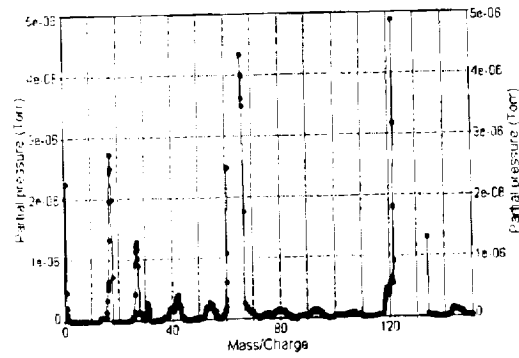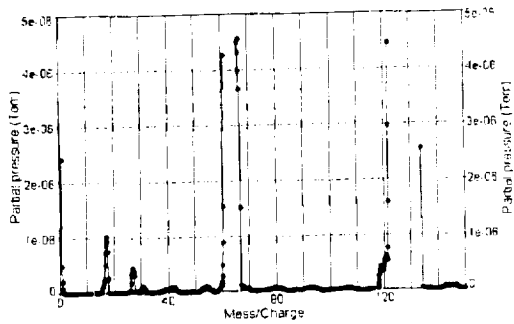
Fig.4. Examples of mass spectra are shown in the following sequence: a)background vacuum; b)chamber filled with xenon; c)xenon plasma with $n_e=10^6$ cm^{-3}; d)arcing on the sample with rate 1 arc/s.
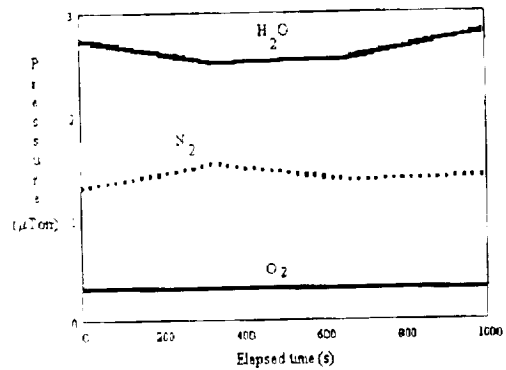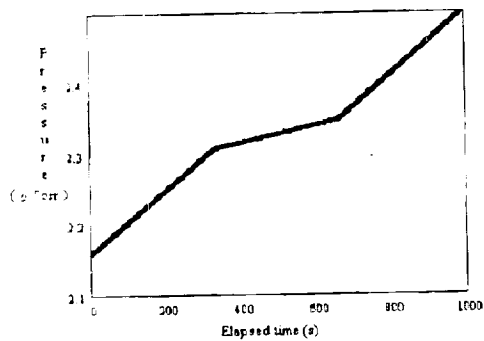

Fig.5. Changes in partial pressure are shown for hydrogen atoms (left panel) and the most abundant molecules (right panel).
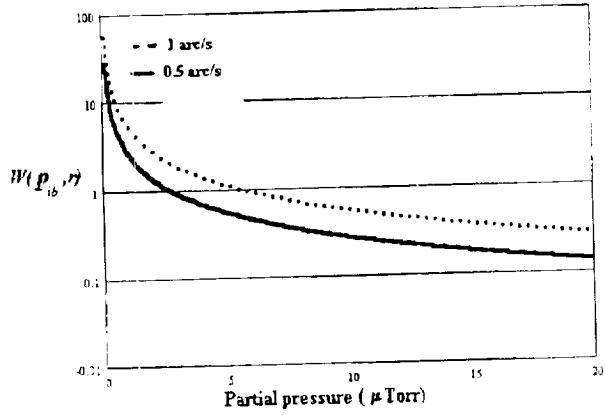
Hydrogen partial pressure

Fig.6. The relative increase of partial pressure due to arcing is shown for two arc rates.
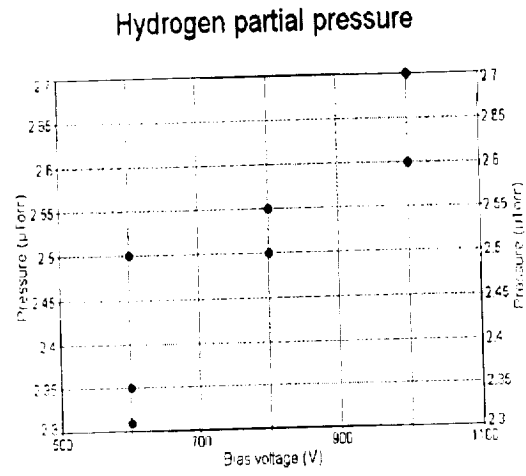
Fig.7. The partial pressure of atomic hydrogen increases significantly with increasing bias voltage.